Sound speed and attenuation in multiphase media. Final Report (N00014-04-1-0164)

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14. ABSTRACT
This report discusses an investigation of the sound speed and attenuation in multiphase media, sandy and muddy sediments, that has shown that a simplified-Biot theory adequately predicts the sound speed and attenuation in sandy sediments with porosities of less than 65%. In addition for muddy sediments with porosities of greater than 70% mixture theory can describe the sound speed. This report discusses the experimental and theoretical basis for these conclusions and related this investigation to other contemporary ONR sponsored research projects. A key finding is the conclusion that in waveguides with a sandy boundary that the effective attenuation obeys a power law with an exponent of 1.8 as proposed by Rosenfeld (2001) and Holmes (2007). Theory predicted a quadratic dependence, exponent of 2. This research has shown that energy removed by shear wave conversion explains this difference, that is the exponent of 1.8 compared to 2. Finally a card house theory was developed to explain the properties of high porosity muddy sediments and that a Mallock-Wood mixture equation describes the slow sound speed.

15. SUBJECT TERMS
Sandy sediments, muddy sediments, microbubbles, sound speed, compressibility, dispersion, shear.

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Abstract

This report discusses an investigation of the sound speed and attenuation in multiphase media, sandy and muddy sediments, that has shown that a simplified-Biot theory adequately predicts the sound speed and attenuation in sandy sediments with porosities of less than 65%. In addition for muddy sediments with porosities of greater than 70% mixture theory can describe the sound speed. This report discusses the experimental and theoretical basis for these conclusions and related this investigation to other contemporary ONR sponsored research projects. A key finding is the conclusion that in waveguides with a sandy boundary that the effective attenuation obeys a power law with an exponent of 1.8 as proposed by Rosenfeld (2001) and Holmes (2007). Theory predicted a quadratic dependence, exponent of 2. This research has shown that energy removed by shear wave conversion explains this difference, that is the exponent of 1.8 compared to 2. Finally a card house theory was developed to explain the properties of high porosity muddy sediments and that a Mallock-Wood mixture equation describes the slow sound speed.

I. Introduction

The important issue addressed was the quantification of the properties of multiphase media; that is: can the mixture be treated as a homogeneous material with effective properties? Whether it is a mixture of air-bubbles in water, water in sand, water in mud or air-bubbles-water in mud, the propagation and attenuation of sound is dependent on the frequency-dependent dispersive characteristic. Quantification of these properties has had naval significance such as the explanation of the "zero Doppler" effect due to sound scattering from micro bubble clouds and the adoption of a nonlinear frequency dependent attenuation factor for bottom loss models.

Originally this research concerned the description of the low frequency, LF, radiation and scattering of sound from compact bubbly mixtures. We showed that such an ensemble of mircobubbles could be described a modified Minneart formula with increased dampening and that a multipole expansion could be used to describe LF the near-sea-surface sound radiation and scattering. The collective oscillation dampening was examined by the careful measurement of the dispersion characteristic of the mixtures. Measurements of the scattering of sound from bubbly-liquids in tubes, bubbly-gels and polyurethane spheres with micro-bubbles were conducted in the laboratory and verified that the monopole resonance could be describe provided the dampening was increased because of thermal, viscous and shear effects. [1,2]

A natural extension was the consideration of the attenuation of sound in sandy sediments. [3-5] Ten carefully conducted shallow water (SW) acoustic transmission experiments in sandy-silty areas with requisite environmental acoustic measurements [6-9] showed that the description of sound transmission in shallow water environments with sandy bottoms

required a site specific nonlinear frequency dependent attenuation. Two such experiments were the Hudson Canyon and ACT II conducted near borehole 6010 on the continental shelf provided a valuable collection of transmission data suitable for inversions and matched field processing . The results of these LF investigations with sandy sediments were universally excellent; however as frequency increased above 100 Hz, large discrepancies were found between measured and calculated sound transmission. Careful numerical analysis that used geophysical measurements and theory to obtain geo-acoustic profiles showed that broad band agreement could only be obtained in the 100 Hz to 1 kHz frequency range provided a value at 1kHz from Hamilton [11], $\alpha(f_o = 1kHz)$, and a nonlinear power-law (n) frequency dependent attenuation was used.

$$\alpha(f) = \alpha(f_o)\cdot(f/f_o)^n$$

Rozenfeld [8] with a summary of carefully selected shallow water experiments and his analysis of transmission loss results, conclude that n=1.8. Holmes [9] extended the collection of shallow water transmission experiments with the constraints of knowledge of bottom properties and favorable comparisons with geoacoustic based computations. He concluded that n=1.8±0.2. Zhou [10] using less restrictive criteria inferred the attenuation versus frequency from a variety of methods such as inversions and range averaged transmission loss to yield 1.8± 0.02. It is important to recognize the fundamental difference between Zhou's approach and of this investigation. The Hazardous Environmental Program, HEP, also observed this nonlinear frequency dependent power-law in measurements. Nevertheless, most naval codes and geoacoustic models still assumed a linear dependence.

A direct consequence of the Biot Theory [12,13,14] is that sandy sediments should have a quadratic dependence, $(n) = 2$. Recent theoretical work [14,15,16] showed that in this lower frequency range that the quadratic power law can be decreased by penetration of the modal functions in the sediment and this predictable change does not account for the observations. The quandary was: why do investigators find exponents n between 1.6 and 1.87 less than 2?

Numerical studies have shown obvious factors such as rough surface scattering and anomalous sound speed profiles due to internal waves cannot explain these observations In particular the Nantucket Sound Experiment sound transmission experiment [17] where roughness and internal waves are not a factor required a power exponent of $n = 1.87$.

The remaining factor to be considered was shear wave conversion. We developed analytical treatment of a SW waveguide with slow shear wave speeds and showed that the rate of energy conversion to shear waves could explain the additional attenuation observed $(\alpha(f) = \alpha_i(f) + \alpha_s)$ at lower frequencies and consequently account for the less than quadratic dependence. The Nantucket Sound experiment was repeated with the same low noise state-of-the-art towed array to determine the characteristic of the interface wave propagation speed from the measured horizontal wavenumber spectra. The observed interface wave speed of ~280 m/s at 275 Hz was sufficient to determine shear could explain this effect and was the first time the interface wave speed has been measured at these high frequencies. [18]

II. Background, the Research Problem

This research project addressed the issue of when sandy and muddy sediments can be treated as a liquid with shear wave conversion treated as another effective attenuation. The analytical treatment of sound scattering from objects on the bottom, partially in the bottom, or buried in the bottom required the specifications of boundary conditions that incorporate both compressional and shear effects. However if a simplified treatment can be demonstrated that allows for compressional wave scattering with increased dampening then the problem will be dramatically simplified.

Previous work was aimed at enhancing our understanding of saturated and partially saturated sandy sediment for frequencies ranging from 100 Hz to 10 kHz. The basic hypothesis was based on the simplified Biot sediment theory [13,15] and the prediction that saturated sands should have a quadratic frequency dependent attenuation, and that measurements can be described by a Biot time constant. Previously, the Nantucket Sound Experiment, [8] we compared this theory to experimental results from an experiment with known environmental (isospeed) conditions, geophysical properties, surface roughness and water depth. While the theory predicted a power-law dependence with an exponent of $n = 2$; results from this experiment agreed with other experiments [8] conducted under similar conditions yielded an exponent on average of approximately

$$\alpha(f) = \alpha(f_o) \cdot (f/f_o)^n; \; n \approx 1.8 \pm 0.2 \text{ with } \alpha(dB/m, 1\,kHz) = 0.33 \pm 0.02, \; [dB/m]$$

The original summary compiled by Rozenfeld [8] used LF shallow water experiments conducted under known and specified conditions. He used exponents determined by the individual investigators. Holmes updated and extended this summary and again used the published exponential factors of the individual investigators. A contemporary survey by by Zhou [9] used results from a larger and less restrictive group of experiments. Zhou used his estimates of the attenuation constant from range averaged transmission loss and inversion results to produce a plot of the attenuation constant versus frequency. An example was the use of the Holmes [17] experiment. Zhou did not use Holmes' estimates of the attenuation but rather the range average transmission loss. His invited ASA paper stated $\alpha(f_o) = 0.34; n = 1.84$ and his published value $\alpha(f_o = 1\text{kHz}) = 0.37 \pm 0.01; n = 1.80 \pm 0.02$. Zhou's result is consistent with the findings of Rosenfeld [8] and Holmes [9] .The attenuation constant $\alpha(f_o)$ is consistent with the 1 kHz results of Hamilton [11].

For long-range propagation when shear is not considered, as is the case for sandy-silty sediments, the modal representation of the pressure field is

$$p(r) \approx \sum_{n=1}^{M} a_n \phi_n(z) \phi_n(z_o) H_o^1[(k_n + i\beta_n)r],$$

where ϕ_n, k_n, and β_n are the eigenfunction, the eigenvalue (or modal wavenumber), and modal attenuation coefficient of the n^{th} propagating mode. A perturbation solution for the modal coefficients that was originally developed by Kornhauser and Raney [19] and revisited by Pierce [13] yields the modal attenuation coefficient as

$$\beta_n(\omega) = (v_{ph,n}) \bullet \int (\alpha(\omega)/\rho c)\phi_n^2 dz / \int (\phi_n^2/\rho)dz$$

This expression shows that the modal attenuation is related to the intrinsic attenuation of the bottom by an integral over depth. Depth dependent profiles should be important in correctly determining the frequency dependence of attenuation. A comparison of the measured pressure field with the pressure field calculated using a normal mode code or with a parabolic-equation code with a depth dependent profiles and frequency dependent attenuation should have explained this less than quadratic dependence.

Calculation with realistic near water sediment gradients in porosity, sound speed and attenuation were found to be inconsistent with these experimental results between 100 Hz and 1 kHz. The conclusion was that geoacoustic gradients could not explain the effect and since the surface roughness was considered negligent ($\sigma \approx 0.01m$); the leakage of sound from the channel by interface waves was considered. The problem was our lack of knowledge of the shear speed in the sandy-silty sediments at frequencies greater than 100 Hz. A review of experimental measurements revealed that the shear wave speed for sandy sediments with porosities in the 40-60% range should be less than 500 m/s. [20,21]

Calculations with parabolic equation and fast field codes were performed [18] to produce simulated pressure versus range data that when analyzed in the same manner as the experiments showed that low sediment shear wave speed could be important in describing the rate of energy dissipation. The results of a calculation performed with a fluid bottom, c_s=0, with $n = 2$ and $n = 1.8$ are shown in Fig. 1.

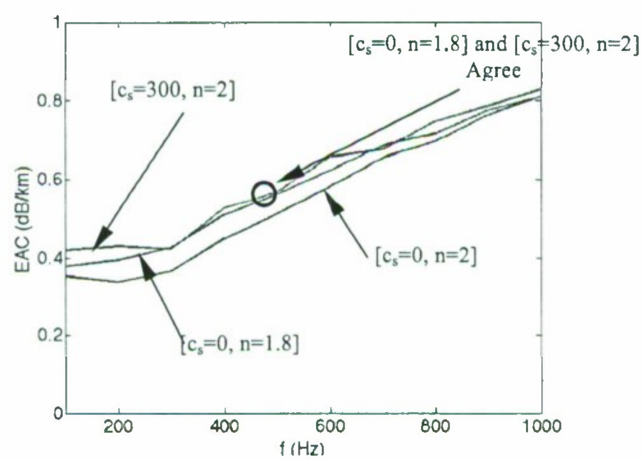

Fig. 1, A comparison of the calculated frequency dependence of the effective attenuation constant, EAC, for a sediment without shear, c_s=0, and with a shear speed of c_s=300m/s with exponents of n=1.8, 2.

The difference in the effective attenuation constant, EAC, is seen to be largest at the lower frequencies. The $n = 2$ results in an underestimate of this factor while the $n = 1.8$ result shows more attenuation at the lower frequencies. However when $n = 2$ is used

with a shear wave speed of c_s=300m/s the results are comparable with $n = 1.8$ result estimated from measurements. [18]

The question posed by this analysis was the value of the shear wave speed in the Nantucket Sound Experiment and was it low enough to explain the $n = 1.8$ result?

An analytical treatment of a two layer waveguide, one being elastic sediment and the other water, showed that the modal attenuation, the removal of energy from the propagating modes, was composed of two terms-intrinsic attenuation and conversion to shear waves, $(\alpha_n(f) = \alpha_{in}(f) + \alpha_{sn})$. Conversion was dependent on the shear wave speed to the third power, c_s^3, and the interface, Sholte, wave should have a speed $c_{sch} \approx 0.9c_s$.

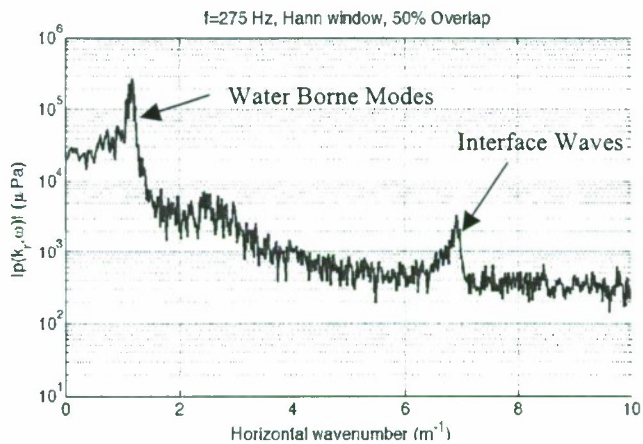

Fig. 2 The measured horizontal wave number spectrum at a frequency of 275 Hz is shown as a linear average of the horizontal wavenumber spectra from six hydrophones.

To determine c_s the Nantucket Sound II experiment [17,18] was conducted with the autonomous-vehicle hydrophone-array system at a constant depth near the bottom on a radial from a bottomed source to a distance of 500 m. The measured complex pressure, $P(r,\omega)$, was then synthetically processed using a Hankel Transform to determine the horizontal wave number spectrum, $P(k,\omega) \cdot P(k,\omega)^*$ that showed the interface wave spectral peak. Fig. 2 shows preliminary results from this experiment. The relative amplitude of the spectral peak of the interface wave to the waterborne compressional waves is ~ 100, (40 dB). The interface wave peak is observed to have a wavenumber of 6.95 corresponding to a shear wave speed of 284 m/s. Nevertheless this measured horizontal wavenumber spectra is an unusual measurement of the sediment shear wave speed. Fig. 3 shows the corresponding result based on an elastic bottom and a fast field calculation.

These results show excellent agreement between our measurements and calculations. Analysis work continues to utilize signal-processing techniques to produce estimates of

the wavenumber spectra at higher frequencies so that the dispersion characteristic can be quantified.

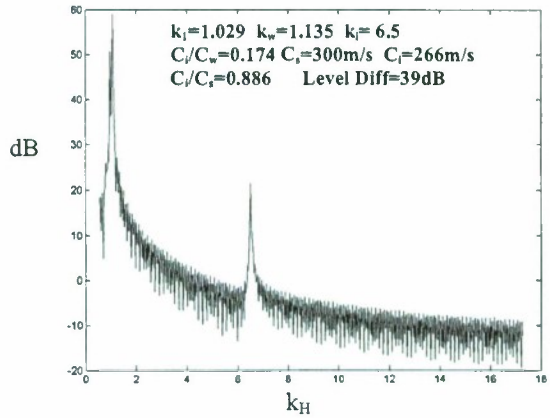

Fig. 3 This figure shows a calculated horizontal wave number spectrum (relative power in dB versus wavenumber) determined by calculation of the complex pressure as a function of range using a fast field code with an elastic geoacoustic profile. The shear wave speed was taken to be 300 m/s and the interface wave speed was determined to be 266 m/s with a level difference of 39 dB.

The autonomous-vehicle towed-hydrophone-array, Avta, system has the inherent capability to be a rapid, accurate and cost effective waveguide characterization tool. The attenuation result from the first, Nantucket Sound I, experiment was found to have frequency dependence $n = 1.87$. Agreement between measured and calculated transmission loss was obtained when this non-linear frequency dependent attenuation with a magnitude consistent with Hamilton's results were used. However the difference between $n = 1.87$ and 2 could not be explained. Numerical calculations and experiments showed that the incorporation of shear yielded results consistent with the measured $n = 1.8$ value. That is leakage of energy into shear wave propagation could explain the measured nonlinear frequency dependence since the apparent attenuation of compression waves in the water would be determine by two effects, the intrinsic attenuation in the sediment and the conversion of compressional waves to shear waves. Since the calculations performed here are in agreement with the measurements and thus illustrate this effect and provide a basis for evaluating the effective attenuation due to shear wave conversion.

Thus the research questions became: can the frequency dependence of muddy sediments and the power law dependence for sandy sediments be quantified by simplified analytical models and verified by refined field measurements on actual sediments from areas of Naval interest? (One such area is the continental shelf on each side of the Hudson Canyon the entrance to New York.) That is to say can we demonstrate the utility of the simplified Biot theory and sound transmission measurements to quantify the frequency dependent sound speed and attenuation factors necessary to describe the reflection from or sound transmission in a waveguide with a bottom composed of sandy and/or muddy

sediments? This quantification of the dispersion is essential to the accurate performance prediction of naval sonar systems.

III. The Research Objectives

Shallow water with sandy-silty bottoms has a nonlinear-frequency-dependent attenuation from the lower to mid frequencies (100 Hz to 10 kHz) . The simplified Biot Theory [13, 14] predicts sandy sediment attenuation with quadratic frequency dependence while muddy sediments should have a linear dependence; however this theory may not be applicable to muddy sediments over the large range of porosities and fine platelet sizes and does not include electro-chemical effects. *Thus the long-range goal was to develop a simplified theory of sandy-muddy sediments that can be applied in areas of naval interest. A second goal is the development a simplified treatment of compressional wave scattering from complex shaped gaseous inclusions and compliant objects in sandy-muddy sediments.*

The first objective was to develop simplified models for selected sandy and muddy sediments that adequately predict the frequency dependent attenuation and phase speed from the lower to mid frequencies. A possible candidate for such a model is the Biot low-frequency model as simplified by Pierce [14,15] and which is consistent with the parameter interpretations made by Stoll [20]. It is not clear whether this model applies to muddy sediments, because the particles in such sediments are primarily clay particles which resemble thin plates and which adopt complex configurations that involve electrochemical forces. Nevertheless, there was an expectation that a suitable simplified model can be devised based on mixture theory.

A second objective is the development of a quantitative understanding and an analytical treatment of the scattering of sound by non-spherical compressible objects such as bubbles in sandy/silty and muddy sediments. Part of this objective was to determine the boundary conditions necessary to describe the sound scattering from microbubble distributions in a multiphase media such as saturated oceanic mud. The current research goal is the development of a quantitative understanding and a theoretical treatment of the scattering of sound by non-spherical compressible objects (microbubbles) in multiphase media in the 1-10kHz region.

IV. Discussion of Results

Calculations of shallow water transmission loss and time spread using geoacoustic profiles agree with experimental results from waveguides with a sandy-silty bottom when site-specific nonlinear factors [n] are used.

$$\alpha(f) = \alpha(f_o)\cdot(f/f_o)^n \ [dB/m]; \quad 1.6 < n < 2.0.$$

At low frequencies, any disturbance in a Biot medium can be represented as a superposition of three basic modal disturbances. With U(x,t) the local spatial average displacement of the *fluid*, and u(x,t) the local spatial average displacement of the *solid*, one finds three modes of propagation:

1.) The Acoustic mode (locked mode, zero curl):

$$\nabla^2 U_{ac} - (1/c^2)\partial^2 U_{ac}/\partial t^2 = -(\tau_B/c^2)\partial^3 U_{ac}/\partial t^3; \quad k \approx \omega/c \;+ i(\tau_B/2c)\omega^2.$$

2.) The Shear mode (locked mode, zero divergence):

$$\nabla^2 u_{sh} - (\rho/N)\partial^2 u_{sh}/\partial t^2 = -[(\rho_{11} + \rho_{12})^2/Nb]\partial^3 u_{sh}/\partial t^3.$$

3.) The Darcy mode (non-locked mode, zero curl):

$$\nabla^2 U_d = k\partial U_d/\partial t.$$

Darcy mode field quantites satisfy this diffusion equation in the first order.

For low frequency acoustic disturbances with a hypothetical sediment intermediate distance (L) much greater than the sediment grain size (a) but much less than the acoustic wavelength (λ), $\{a << L << \lambda\}$, the motion is nearly uniform over distances of order L and displacements of fluid and solid portions nearly the same, a no-slip condition results in

$$\alpha(\omega) = K \cdot \omega^2 \;;\; K = (\beta a^2 \rho_{eff}/2c_{eff}\eta) \cdot ((\rho_s - \rho_f)/\rho_{eff})^2 \chi_s^2 \chi_f.$$

Proportionality to frequency-squared at low frequencies is very fundamental, easy to derive from causality considerations The inverse proportionality to viscosity (η)was "sort of implicit" in Biot's original heuristic theory, but not widely appreciated. the proportionality to square of density difference $(\rho_s - \rho_f)^2$ is fundamental result of the viscous partial retardation mechanism and can by tested by laboratory experiments. The positive dimensionless number β can be estimated by sophisticated computation. While the theory predicts a power-law dependence with an exponent of $n = 2$, results from experiments conducted under similar conditions yielded an exponent on average of

$$\alpha(f) = \alpha(f_o) \cdot (f/f_o)^n; \quad n \approx 1.8 \pm 0.2 \text{ with } \alpha(dB/m, 1\,kHz) = 0.33 \pm 0.02,\ [dB/m].$$

This summary of experimental results [8,9] is consistent with the measurements of Hamilton [11] at 1 kHz.

An analytical treatment of a waveguide with a water layer (ρ,c) over a sediment (ρ_b ,c_b) with a slow shear wave speed ($c_s < c < c_b$) shows that the rate of energy conversion to shear waves could explain the apparent additional attenuation, $\alpha_a(f) = \alpha_{swc} + \alpha_i(f)$. Here α_{swc} describes the removal of energy from the water borne field by shear waves. At higher frequencies ($\alpha_a(f) \approx \alpha_i(f)$) while at lower frequencies ($\alpha_a(f) \approx \alpha_{swc}$), thus the observed effective attenuation is determined by a power law relationship between these asymptotes with a less than quadratic dependence. This effective shear wave attenuation can be shown to be proportional to the cube of the shear wave speed, c_s^3 [13]. Hamilton [11] and Stoll [20] report shear wave speeds between 100 to 300 m/s for sandy sediments with porosities of 40-50%. Hastrup [21:121-127] reports empirical relationships that

relative speed ratios $1.0 \le c_b / c \le 1.079$ yield shear wave speeds $184 \le c_s \le 400\ m/s$. While the actual value of the shear wave speed and gradients in the first 5.5 m of sediments are largely unknown, these estimates indicate that the attenuation due to shear wave conversion can vary by a factor of 64. Nevertheless it is possible to quantify the attenuation, $\alpha_a = \alpha_{wc}(f,z) + \alpha_i(f,z)$, and to represent the attenuation by the power law $\alpha_a = \alpha_i(f_o)(f/f_o)^m$ where m is a site-specific exponent used to account for shear wave conversion. This enables the representation of the bottom as a fluid with a site specific attenuation.

Our investigations on bubbly liquids and scattering of sound from microbubbles and distributions compared bubbles surrounded by liquids to those in synthetic gels and urethanes. These investigations showed that the presence of a gel or viscoelastic material had the effect of increasing dampening. Experiments conducted in a muddy pond bottom [23] showed the effect of methane microbubbles on the sonic speed and reverberation. A card house theory [24] was adapted to describe mud with considerable water volume fraction. The description of bubble scattering in mud in the 1-10kHz is currently being investigated to describe the effect of methane microbubble distributions on sound speed and attenuation.

V. Summary of Results

Sandy/silty marine sediments are water saturated and consist of diverse tiny rock pebbles. The weight of higher pebbles holds lower pebbles in contact. For low frequency acoustic disturbances, the no-slip condition and viscosity cause the local water displacement near solid surfaces to be nearly the same as that of the neighboring pebbles. Water further from surfaces oscillates relative to solid matter because of mass density difference, and viscosity limits the oscillation amplitude. Derived dissipative-wave equation was shown to predict attenuation proportional to frequency squared, proportional to the square of the difference of the densities, and inversely proportional to viscosity.

Transmission measurements yielded intrinsic attenuation estimates for acoustic waves in the underlying sediment, with results that are consistent with attenuation being proportional to frequency raised to a power n, with $n \approx 1.8$. Plausible theory suggests n should be identically 2. The discrepancy can be explained, because the inverse analysis inferences neglected an additional attenuation mechanism where generated lower velocity shear waves carry energy downwards out of the waveguide. This shear effect has a weaker dependence on frequency than the intrinsic attenuation, so the apparent exponent is shifted downward [18].

Muddy sediments with large porosities were found to have s lower sonic sped than expected and considerable time spread. Methane mircobubbles can affect the sonic speed in muddy sediments. This decrease in sonic speed was found consistent with expectations based the Mallock-Wood equation. These bubbles can also scatter sound and produce time spread.

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